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WASATCH NATIONAL FOREST

ALTA AVALANCHE STUDY CENTER

TRANSLATION NO. 6

AVALANCHE FORCES AND THE PROTECTION OF OBJECTS

by

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Lawinenkraefte und Objectschutz

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Translated by E. LaChapelle

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1. Introduction

This contribution is addressed primarily to the practical man who comes into contact with the problems of avalanche effects on structures in the course of his professional work in the mountains. An attempt is made to estimate avalanche forces by assembling a number of relatively simple formulas. But a certain experience and familiarity with snow and avalanches are still assumed for an intelligent treatment of the subject.

The following exposition is based on the latest available theoretical studies, on current experience from test installations of the Institute for Snow and Avalanche Research (SLF), and on the study of specific problems in the Swiss Alps.

B. Salm: Contribution to avalanche dynamics. Mitteilung Nr. 24 des Eidg. Instituts für Schnee- und Lawinenforschung vom Februar 1966

B. Salm: Lawinenwirkung und bauliche Schutzmassnahmen. (Avalanche effects and construction measures for defense.) Referat anlässlich eines Lawinenzonen-Kurses vom 8./9. Nov. 1962 (Unpublished)

A. Voellmy: Ueber die Zerstörungskraft von Lawinen. (On the destructive force of avalanches.) Sonderdruck aus der Schweiz. Bauzeitung, 73rd year, Vol. 12, 15, 17 and 37 (1955) Available in English as Transl. No. 2, U. S. Forest Service Alta Avalanche Study Center.

As a rule, these cited works deal with simple avalanche models in which are introduced materials constants for static and moving snow whose numerical values are only partly known.

For this reason a high degree of accuracy cannot be assigned to

the results obtained up to this time. The practical problems are often complex and from case to case have to be adapted to the formulas.

A thorough treatment of the whole subject would lead far afield and, moreover, is not the purpose of this manual. Those more deeply engaged in avalanche problems who want to delve further into the subject will refer to the pertinent literature.

2. Problems

Structures often have to be protected from damaging avalanche effects by constructive measures directly at the protected object or in its immediate vicinity.

- reinforced walls
- backfills
- wedges
- deflection walls
- roofs
- snow sheds, etc.

The protective structures conform to the expected loading from static and moving snow. In calculating these forces, exceptional avalanche conditions have to be considered on one hand, but on the other it often is not possible on financial grounds to allow for the maximum conceivable conditions when calculating the normal permissible loads. For such cases it is necessary to turn to the normally employed safety factors. There will be a certain residual, unpro-

tected risk which those in charge of the construction have to take into account and allow for.

3. Preparatory Work

3.1 Field Check

- Inspection of the locality. (All the important features cannot be seen on a map or plan.)
- Investigate terrain forms and exposure clear up to the avalanche fracture zone.
- Listen to statements of local residents, but accept these critically.

3.2 Study of Records

- Snow depths, weather influences (wind, temperature, etc.) from existing records of nearby stations.
- Reports of earlier avalanche activity (possibly old records or chronicles).

3.3 Determinations from Maps or Overall Plan

- formation zone
- fall path
- deposition zone

altitudes, height differences, sizes, areas, slopes

Figure 1 gives an example in 100-meter steps of height differences.

Example with 100m vertical differences:

Elevation Range (m)	Vertical Difference (m) HD	Horzontal Difference (m) a	Tangent of Slope Angle ψ (degrees)	Length of Slope (m) b	Width (m) c	Area (m^2) bxc
1140-1200	60	150	22	162	100	16,200
1200-1300	100	160	32	188	100	18,800
1300-1400	100	175	30	220	100	22,000
1400-1500	100	200	27	225	250	56,200
1900-2000	100	137	36	169	200	33,800
Sums and Averages	860		34^{o} (Avg.)	1374		228,200

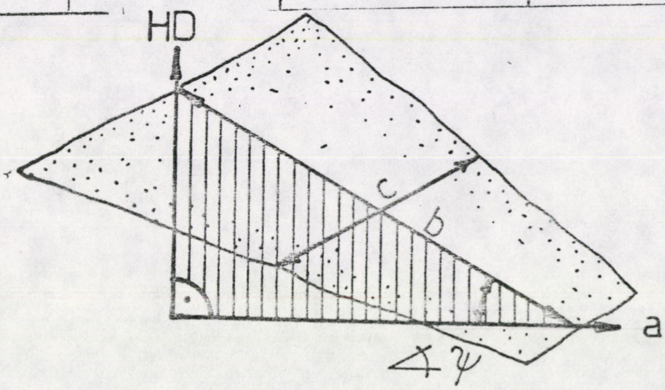


Figure 1

3.4 Judging the Profile Forms

Establishment of a longitudinal profile along the entire avalanche path (overview!)

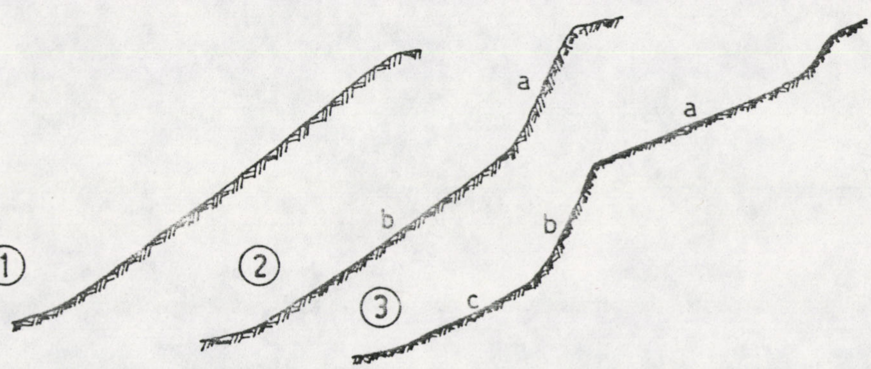


Figure 2

1 - even fall path (or track):

2 - Outrun zone bounded above by a steep section:

- the snow cover at "b" is stabilized by "a", thus as a rule exceptionally heavy snowfalls are not cause for alarm.

3 - steep section in the fall path (or track):

- large snow deposits are possible at "a", dry loose snow avalanches develop into powder avalanches at "b".

Many loose snow avalanches occur on slopes steeper than 40° to 45°. As a rule, the slopes unload themselves in succession, especially when they are interrupted by a steep cliff band.

Fall path cross-sections:

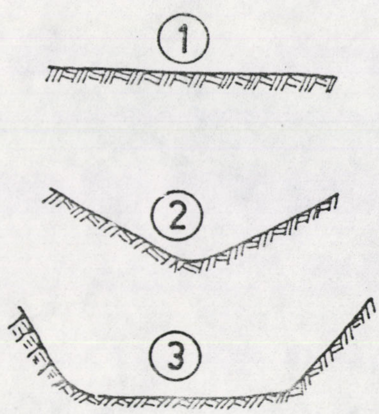


Figure 3

1 - slope (non-channelized)

2 & 3 - gulley forms (augmented friction) - gulley avalanches with a large depth of flow (channelized)

4. Assumptions

4.1 Possible or Noteworthy Avalanche Characteristics

Avalanche situations:

- persistent snowfall

- poor snow cover development
- snow cover wet throughout
- local snow accumulation by wind transport

Avalanche types:

- powder avalanches
- dry, loose-snow avalanches

$\left.\begin{array}{l}\text{powder avalanches}\\ \text{dry, loose-snow avalanches}\end{array}\right\}$ mid-winter

- wet, loose-snow avalanches, ground avalanches - spring

4.2 Standard Avalanche Situations: A given thickness of the sliding snow layer over the entire release zone is assumed for the various situations.

- Normal: d_o = 50 cm for the fundamental planning (e.g., snow removal from mountain highways, avalanche zoning plans).
- Unusual: d_o = 120 cm for force calculations
- Extreme: $d_o >$ 120 cm is seldom allowed for (catastrophes)

4.3 Location of the Protected Objects.

- directly in the track of the avalanche; the object is exposed to all types of avalanches.
- In the run-out zone (deposition area): velocities are reduced, but the deposited masses of avalanche snow have to be considered.
- in the edge zones, on elevated sites: object outside the sliding and deposition zones, possibly exposed only to air blast.

4.4 Bases for the Calculations

Definitions:

d_o thickness of sliding snow layer in the starting zone (m)

γ_o average density of the naturally deposited snow (kg/m^3)

γ_1 density of the sliding (flowing) snow (kg/m^3)

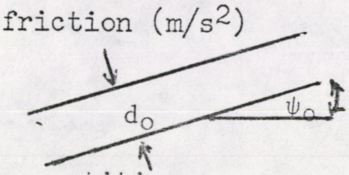
ψ_o slope of the terrain in the starting zone (°)

ψ_u slope of the terrain in the effects zone (°)

ξ coefficient of ground friction (m/s^2)

μ friction coefficient

ψ_o	d_o
28°-30°	~1.40m
31°-33°	~1.30m
34°-36°	~1.20m
37°-39°	~1.10m
40°-42°	~ .80m
>45°	~.50-.6



Assumptions about the individual quantities:

Unusual avalanche conditions

d_o = 1.2 m for normal slope profile and normal deposition (possibly higher assumed value for wind drift areas and short slopes).

= 0.5 m for slopes broken by cliff bands

γ_o	Loose new snow	30 - 150 kg/m^3
	Felt-like snow	100 - 300 kg/m^3
	Round-grained old snow	200 - 600 kg/m^3
	Angular-grained snow (depth hoar)	150 - 500 kg/m^3

γ_1 No measurements available. Estimate based on theoretical evaluation.

Flowing avalanches in general	$\gamma_1 \sim \gamma_o$
Dry flowing avalanches	$\gamma_1 < 300\ kg/m^3$
Wet flowing avalanches (ground avalanches)	400-500 kg/m^3

γ_1	Powder snow avalanches $\sim 2 - 30$ kg/m^3 possible calculation according to Voellmy (somewhat higher values) $\gamma_1 = \frac{\gamma_L}{2g} \cdot \xi \cdot \sin \psi$ $200 \leq \xi \leq 300 m/s^2$ air density $\gamma_L = 1.25$ kg/m^3 * acceleration of gravity $g \sim 10$ m/s^2
ψ_o, ψ_u	Taken from a map or measured on the ground.
ξ	Mean value = 500 m/s^2 (according to A. Voellmy). Varies from 400 to 600 m/s^2 according to the roughness of the ground surface (analogy with hydraulics) - gulley, thin tree cover = 400 m/s^2 (dry flowing avalanche) - smooth slopes (long grass) = 600 m/s^2
μ	Important factor! The correct loading assumptions depend heavily on its measurement. For velocity calculations: $\mu = 0$ to 0.3 (flowing avalanches mostly 0.15-0.3) For shear force calculations: $\mu = 0.4$ to 0.5 Flowing avalanches: $\mu = \frac{\gamma_o}{2000}$ (γ in kg/m^3) Powder avalanches $\mu \rightarrow 0$ Very wet avalanches $\mu \rightarrow 0$ (advance over very gently sloping terrain possible)

* $\gamma_L \approx 1.0$ for Colorado and other locations where elevation $\geq$ 10,000 feet (3000m)

5. Calculations

d_1	thickness of the flowing avalanche (m)
v	avalanche velocity (m/s)
d_a	mean depth of avalanche deposit (m)
s	outrun path of the avalanche (m)
s_o	inrun path of the avalanche (m)
P_{nd}	deflecting force (kg)
p_{nd}	specific deflecting force (kg/m^2)
p_n	total specific normal load (kg/m^2)
P_{sd}	friction force (deflection) (kg)
p_{sd}	specific friction force (kg/m^2)
p_s	total specific shear force (kg/m^2)
P_{stat}	static snow pressure (reverse flow) (kg)

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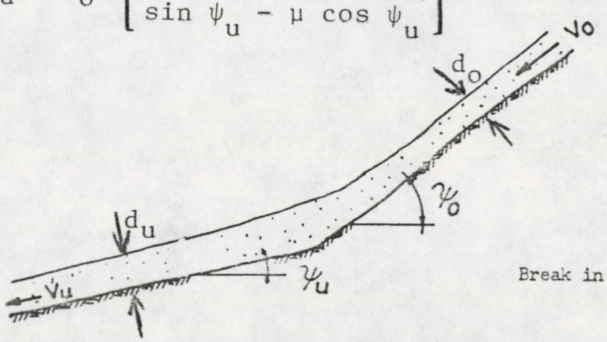
d_1 Slopes without significant breaks

- flowing avalanches $\qquad d_1 \sim d_o$
- powder avalanches $\qquad d_1 \cong \frac{\gamma_0}{\gamma_1} \cdot d_o$

For slope breaks:

$$d_u = d_o \left[\frac{\sin \psi_o - \mu \cos \psi_o}{\sin \psi_u - \mu \cos \psi_u} \right]^{1/3}$$

Figure 4



Break in slope

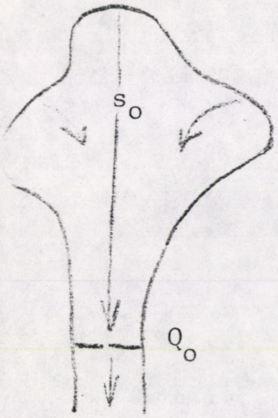
Velocity: $V_o = \sqrt{\xi \, d_o \, (\sin \psi_o - \mu \cos \psi_o)}$ Should be with Gullies Top of page 10

(let $\mu = 0.15$)

d_1 Gulleys:

d depends on the form of the gulley cross-section and the discharge of flowing snow, Q

Starting Zone



Measured Values:

ψ_o = avg. slope
d_o = avg. thickness
$s_o = s_{max}$
$F_o = \frac{\text{map area}}{\cos \psi_o}$

Computed Values

K_o
v_o (v average)
Δt
Q_o (Q average)

a) determination of the snow discharge, Q_o from the starting zone

$$v^2 = \xi \, d_o \, (\sin \psi_o - \mu \cos \psi_o)$$

$$Q_o = \frac{K_o}{\Delta t} \quad (m^3/s)$$

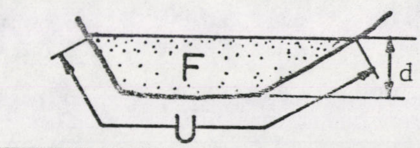
where volume of moving snow, K_o, is

$$K_o = d_o \, F_o \quad (m^3)$$ [F_o = map area of avalanche in starting zone/$\cos \psi_o$]

and time difference, Δt is

$$\Delta t = \frac{s_o}{v_-} \quad \text{(sec.)}$$

b) Graphic determination of d_1 for a given gulley cross-section:



GULLEY CROSS-SECTION

d	F	U	$R = \frac{F}{U}$	$v^2 = (\sin \psi_u - \mu \cdot \cos \psi_u) \xi \cdot R$	$v \cdot F = Q$
d_1				→	Q_1
d_2				→	Q_2
d_3				→	Q_3

Assume different values of d ($d_1 \ldots . d_n$). Use these to calculate different flow quantities $Q_1 \ldots . Q_n$, using the hydraulic radius. The value of Q_i which corresponds to Q_o gives the sought value of d_1 as well as v_1.

F = cross-section area of gulley [often referred to as A]

U = circumference of ground surface affected by avalanche

R = hydraulic radius

Q = snow quantity (discharge quantity)

b_m = mean avalanche width

Slope break in gulleys:

$$R_u F_u^2 = \frac{(\sin \psi_o - \mu \cos \psi_o)}{(\sin \psi_u - \mu \cos \psi_u)} R_o F_o^2$$

The desired flow thickness, d_u, is obtained by trial in analogous manner with the table for calculating flow thickness in gulleys. The subscript u refers to gulley below the break; o to gulley above the break.

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v_1

Flowing avalanche:

-Gulley (according to Salm):

$$v^2 = \xi R (\sin \psi - \mu \cos \psi) \qquad \text{see under } d_1$$

-Slopes:

$$v^2 = \xi d_1 (\sin \psi - \mu \cos \psi)$$

$$v^2_{max} = \xi d_1 \sin \psi \qquad (\mu = 0)$$

The maximum velocity is acheived over a relatively short part of the path!

$$s_o \sim 25 d_1$$

-Powder avalanche:

$\gamma_o \sim 80-100 \text{ kg m}^{-3}$

$$v^2 = 2g\, d_o \frac{\gamma_o}{\gamma_L} \qquad \gamma_L = 1.25 \ (\text{kg/m}^3)^*$$

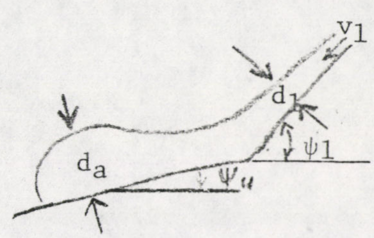
Limits of the mean deposition depth: d_a

d_a

$$d_1 \le d_a \le d_1 + \frac{v_1^2}{4g}$$

when

$$d_a = d_1 + \frac{v_1^2}{4g\, \lambda_\rho \cos \psi_u}$$



λ_ρ, Salm's resistance factor, varies from 2 to 3

[Editorial comment: use 2 when debris cannot spread laterally; 3 when it can].

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*Use $\gamma_L \cong 1.0$ for Colorado and other locations where elevation $\geq$ 10,000 feet (3000 m)

s Outrun path (after Voellmy--Salm gives more uncertain values, but the formula does not lend itself to approximations).

--does the object lie within the avalanche path?

--forces reduced?

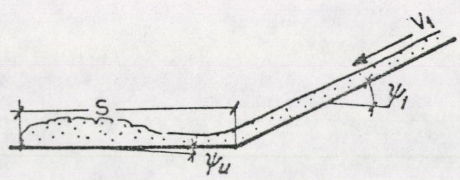
--deposition of avalanche snow? etc.

$$s \sim \frac{V_1^2}{2g\left[(\mu \cos \psi_u - \tan \psi_u) + \frac{V_1^2}{2\xi d_a}\right]}$$

for $\psi_u \leq 12^o$
use $0.2 \leq \mu \leq .25$
(catastrophic avalanches)

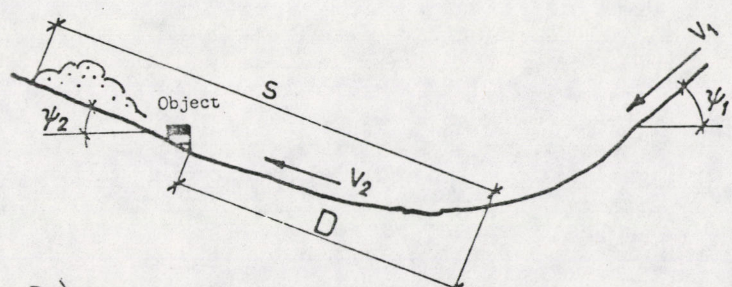
when the expression within the parenthesis in the denominator is

- > 0 -finite runout zone (avalanche comes to a stop)
- ≤ 0 -infinite runout (avalanche does not stop)



In the case of ascending outrun:

$$S \sim \frac{V_1^2}{2g\left[(\mu \cos \psi_2 + \tan \psi_2) + \frac{V_1^2}{2\xi\, da}\right]}$$



$$V_2^2 = \left(1 - \frac{D}{S}\right) V_1^2$$

[Editorial note: The "tan ψ" term in the runout equations should be "sin ψ". This is an error carried over from the original Voellmy work. For small angles the numerical difference between tan and sin is insignificant.]

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6. Force Calculations

--For exposed structural parts, an upward vertical force in addition to the pressure in the direction of avalanche impact has to be considered:

$$p_v \sim 0.5\ p_h \quad (h = \text{horizontal})$$

--The protective structures are stressed to the height of the avalanche.

--The deposited (natural or by avalanche) snow masses have to be considered as well as the moving ones.

--Ramming effects of transported foreign bodies (stones, timber, etc.).

--The damaging effect of wind blast is light, maximum 0.5 t/m^2.

--0.1 - 0.2 t/m^2 is sufficient to break in windows or weak doors.

The Important Types of Loading

(see next page)

THE MOST IMPORTANT TYPES OF LOADING

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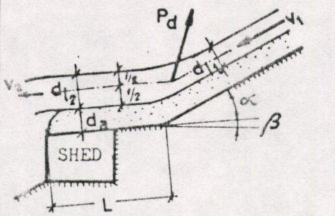
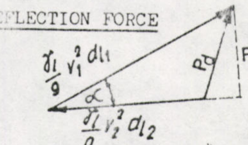
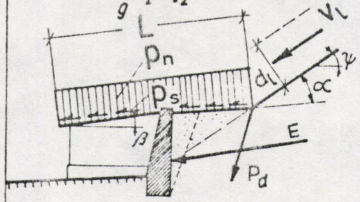
<td>p_n</td>
<td>


DEFLECTION FORCE



NORMAL AND THRUST FORCE
</td>
<td>
α DEFLECTION ANGLE
β ROOF SLOPE
L DEFLECTING ZONE
d_a SNOW DEPOSITION THICKNESS
d_l AVALANCHE THICKNESS
μ FRICTION COEFFICIENT (0.5)
<hr>
DEPOSITED SNOW:
$p_{na} = \gamma_a d_a \cos\beta$
AVALANCHE LOAD:
$p_{nl} = \gamma_l d_l \cos\beta$
DEFLECTION FORCE:
$p_{nd} = \frac{d_l}{L}\frac{\gamma_l}{g} v_l^2 \sin\alpha$
TOTAL NORMAL FORCE:
$\boxed{p_n = p_{na} + p_{nl} + p_{nd}}$
</td>
</tr>
<tr>
<td>p_s</td>
<td>
$E > P_d$ (as a rule)
E = EARTH PRESSURE
P = AVALANCHE DEFLECTION FORCE
</td>
<td>
STATIC LOAD:
$p_{sa} = \gamma_a d_a \sin\beta$
DYNAMIC AVALANCHE LOAD:
$p_{sl} = \mu p_{nl}$
DEFLECTION FORCE:
$p_{sd} = \mu p_{nd}$
TOTAL THRUST FORCE:
$\boxed{p_s = p_{sa} + p_{sl} + p_{sd}}$
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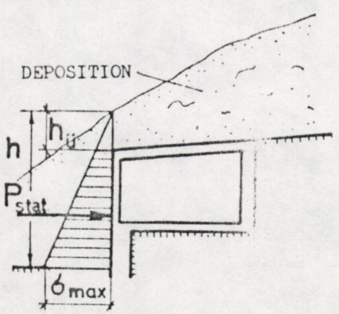
<tr>
<td>$P_{stat.}$</td>
<td>


</td>
<td>
$P_{stat.} = \frac{\gamma (h^2 - h_ü^2)}{2(m-1)}$
$\sigma_{max} = \frac{2P_{stat.}}{h}$
MATERIAL CONSTANT m:
ICE m = 2
HARD SNOW m = 4-5
NEW SNOW m = 50
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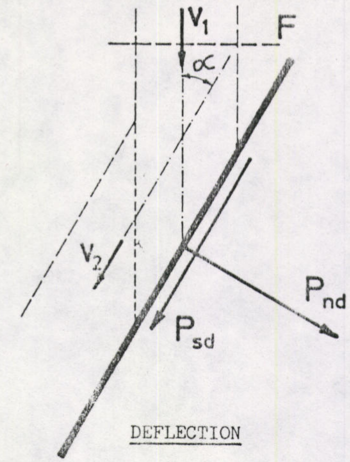
<table>
<tr>
<td>P_{nd}
P_{sd}</td>
<td>


DEFLECTION
</td>
<td>
$P_{nd} = \frac{\gamma_l}{g} F V_1^2 \sin\alpha$ (kg)
$P_{sd} = \mu P_{nd}$ (kg)
$\mu = 0.5$ FRICTION COEFFICIENT
SNOW-SNOW, SNOW-CONCRETE
F = SURFACES PERPENDICULAR TO V_1
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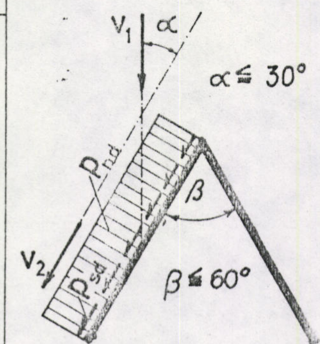
<tr>
<td>p_{nd}
p_{sd}</td>
<td>


WEDGE
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<td>
SPECIFIC DEFLECTION FORCE:
$p_{nd} = \frac{\gamma_l V^2}{g} \sin\alpha^2$ (kg/m²)
$p_{sd} = \mu p_{nd}$ (kg/m²)
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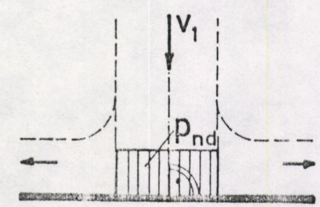

PERPENDICULAR TO WALL
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<td>
$p_{nd} = \frac{\gamma_l V_1^2}{g}$ (kg/m²)
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